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Simulation of Double-Bang Event in the Atmosphere

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Abstract

We use CORSIKA+Herwig simulation code to produce ultra-high energy neutrino interactions in the atmosphere. Our aim is to reproduce extensive air showers originated by extragalactic tau-neutrinos. For charged current tau-neutrino interactions in the atmosphere, beside the air shower originated from the neutrino interaction it is expected that a tau is created and may decay before reaching the ground. That phenomenon makes possible the generation of two extensive air showers, the so called Double-Bang event. We make a quantitative analysis of the main characteristics of the Double-Bang events in the atmosphere and conclude that it may be possible to observe this kind of event in ultra-high energy cosmic ray observatories such as Pierre Auger.

Introduction

It is believed that neutrinos with energies of the order of 10^{18} eV (1 EeV) arrive at the Earth from extragalactic sources and may interact with the nuclei in the atmosphere generating cascades of particles called Extensive Air Showers (EAS's) [1]. There are basically two methods to detect those EAS's: one is to detect the particles when they reach the ground through water tanks equipped with

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photomultipliers [2, 3]. The photomultipliers are used to detect the Cherenkov light emitted by the ultra relativistic particles when they cross the water inside the tanks. By spreading the Cherenkov tanks in a big and plane area it is possible to determine the distribution of particles when the EAS reach the ground and with this information to determine the direction and energy of the incident particle that generated the event. The other method is to observe the scintillation light of the atoms which are excited during the developing process of the EAS [3, 4]. The atoms emit detectable visible and ultraviolet light when they return to their ground states. The detectors used for this method are called Fluorescence Detectors (FD's) because of the similarity of the scintillation with the fluorescence light. This technic of detection can be used to measure the profile of the EAS when it develops through the atmosphere.

To distinguish which particle have generated an EAS is not an easy task, but we can take advantage of the different depth of the atmosphere depending on the zenith angle. While for vertical angles the atmospheric depth is approximately 1000 g/cm^2, for horizontal angles it is approximately 36000 g/cm^2. Neutrinos, because of their very low cross section and mass, are the only particles beside the muons that can go deep in the atmosphere before interacting or decaying. In these way it is possible that neutrinos come from very near horizontal angles and interact close to the detector. Ordinary particles when come from almost horizontal angles interact in the top of the atmosphere and when the EAS generated arrives at the detector, it has basically the muonic component because the hadronic and electromagnetic components were absorbed by the atmosphere [5]. From the other side, neutrinos may generate EAS's near the detector and therefore they still contain the electromagnetic and hadronic component. Furthermore an EAS generated close to the detector has a curved and thick front of propagating particles, while an EAS generated far from the detector, when arrives at it has a thin and almost plane front of particles [6]. With detectors sensitive to the EAS's components and the geometry of the front of particles of the EAS, it is possible to determine if it was generated near or far from the detector and consequently, if it was generated by a neutrino or not.

The case of tau-neutrinos is even more special. First of all, because it is not expected that tau-neutrinos are created in extragalactic sources. Tau-neutrinos are due to neutrino oscillation during the propagation from the source to the detector [7]. Then when the tau-neutrino interacts via charged current (CC) in the atmosphere it creates an EAS which contains a tau. This tau decay in a distance comparable to the size of the EAS and almost all of the times it generates another EAS that may also be detectable. This kind of unique signature is named Double-Bang signature and our aim in this paper is to investigate through simulations the main characteristics of tau-neutrino induced events in the atmosphere.

1 Ultra-High Energy Neutrino Induced Events

Consider a neutrino arriving at the Earth and interacting via CC with a nucleon in the atmosphere generating a charged lepton and other fragments:

$$\nu_l + N \rightarrow l + X \,, \tag{1}$$

where l is the lepton flavor (e, μ, τ). For a neutral current (NC) interaction another neutrino is created rather then a charged lepton.

After the CC interaction, the neutrino energy is divided between the charged lepton and the rest of the fragments that generate the EAS in the following way:

$$E_\nu = E_1 + E_l \,, \tag{2}$$

where E_ν is the incident neutrino energy, E_1 is the energy deposited in the fragments that generate the EAS and E_l is the charged lepton energy.

Because the energy distribution varies for each interaction, it is interesting to define the inelasticity, that is the fraction of the neutrino energy that goes to the EAS and not to the charged lepton. The inelasticity is:

$$y = (E_\nu - E_l)/E_\nu \,. \tag{3}$$

Combining Eqs. (2) and (3) we have:

$$E_1 = yE_\nu \,, \tag{4}$$

and finally from Eqs. (2) and (4) we find the neutrino energy fraction transfered to the charged lepton:

$$E_l = (1 - y)E_\nu \,. \tag{5}$$

When a muon-neutrino interacts via CC, it creates an EAS with the same characteristics of the ones produced via NC interactions for any neutrino flavor. It is because similarly to the neutrinos created after the NC interactions, the muon created after a CC muon-neutrino interaction almost does not interact with the atmosphere [8] and for the energies considered, the muon decay length is much longer than its interaction length.

Electron and tau-neutrino CC interactions are completely different. The electron, created after the electron-neutrino interaction, interacts immediately generating a cascade of electromagnetic particles beside the hadronic component generated by the other fragments created in the first interaction. The tau created after the tau-neutrino interaction propagates in a very similar way to the muon, but its mean lifetime is much shorter. For the energies considered the decay length of the tau is of the order of few tens of km in the laboratory frame, comparable to the length of the hadronic EAS created. When the tau decays, it may generate a second hadronic shower and both showers together generate a sign characteristic of tau-neutrino interactions only.

2 Tau Neutrinos

First we discuss the well known case in which the tau-neutrinos interact inside the Earth and after that we introduce our propose in which tau-neutrino interacts in the atmosphere generating Double-Bang events.

Electron and muon-neutrinos with energies higher than 1 PeV interacting inside the Earth are absorbed [10], but a tau-neutrino suffers a regeneration process creating another tau-neutrino in such a way that the Earth becomes transparent for this neutrino flavor. For NC interactions the energy of the tau-neutrino created is approximately one half of the energy of the initial tau-neutrino. In a CC interaction a tau is created and the energy of the tau-neutrino resulting from the tau decay is approximately one fifth of the energy of the initial tau-neutrino. When the tau-neutrino energy arrives to the level of 10-100 TeV, bellow the absorption limit, its interaction length is of the order of the Earth diameter and the neutrinos propagate freely.

The amount of neutrino energy absorbed also depends on the portion of matter traversed, and consequently, on the incident angle. Consider the geometry in which $90°$ corresponds to a neutrino that crosses the Earth passing through its center and that smaller angles correspond to the chords crossing points not diametral opposites. For angles smaller than $5°$, that are almost tangent to the surface of the Earth, the neutrinos cross a little amount of matter and conserve relatively high energies, of the order of 1 EeV. It is possible that taus scape from the Earth and decay near the surface generating detectable almost horizontal EAS's. This kind of event is called Earth Skimming. Another possibility, with almost the same physics, exists when neutrinos traverse mountains generating taus that scape and propagate downwards almost horizontally in the atmosphere decaying near the surface.

In the Pierre Auger Observatory [11] context, many articles have been published analyzing the potential of the detectors of this observatory to detect neutrinos [6, 12] and specially Earth Skimming [13] events. Based on estimated neutrino flux coming from Active Galactic Nuclei [14, 15], Gamma Ray Bursts [16] and Topological Defects [15, 17], as well as on neutrino cross section extrapolated to ultra-high energies [18], it is expected a number of around one event per year with energies of the order of 1 EeV.

Based on the propose of John Learned and Sandip Pakvasa [19] to detect tau-neutrinos with energies of the order of 1 PeV in detectors under water or ice, it has been proposed to use FD's to detect tau-neutrinos with energies of the order of 1 EeV interacting in the atmosphere [20]. After it is created the tau propagates, before decaying in the laboratory frame, a distance given by:

$$L = \gamma c \tau \,, \tag{6}$$

where γ is the Lorentz factor and τ is the tau mean lifetime. In terms of the energy given in units of EeV, we have that the distance traveled by the tau in the laboratory frame is:

$$\begin{aligned} L &\simeq \frac{E_\tau}{[\mathrm{EeV}]} \times 49 \text{ km}\,, & (7)\\ &\simeq (1-y)\frac{E_\nu}{[\mathrm{EeV}]} \times 49 \text{ km}\,. & (8)\end{aligned}$$

In our simulations we consider only the case of hadronic decay, despite we could have considered also the electronic decay which corresponds to almost 18% of the tau decay branching ratio [9]. Only the hadronic branching ratio is responsible for 64% of the tau decays. Based on the hadronic branching ratio of the tau decay, that is basically decay to pions, we consider that the energy of the second EAS, originated by the tau decay, is in average:

$$\begin{aligned} E_2 &\approx \frac{2}{3}E_\tau\,, & (9)\\ &\approx \frac{2}{3}(1-y)E_\nu\,. & (10)\end{aligned}$$

3 Simulations

There are no experimental data confirmed of Ultra-High Energy (UHE) EAS generated by neutrino. Monte Carlo simulations are an important tool to study the characteristics of UHE events that may be generated by neutrinos. Through simulations, the longitudinal development of the charged particles in the atmosphere can be studied in a systematical way. In general, the EAS longitudinal development depends on the energy and the type of the primary particle, as well as on the interaction depth and the incident angle in the atmosphere.

A study of the characteristics of the UHE EAS's generated by electron and muon-neutrinos was made in [21] through CORSIKA [22] simulations. CORSIKA itself is not able to simulate neutrinos as primary particles, so the neutrino interaction is made by Herwig [23] and then, the results of this interaction are taken by CORSIKA as the primary particles which give rise to the EAS. Until the present moment, simulations with tau-neutrino as primary particle and the decay of taus in CORSIKA+Herwig are not available. Because of that we simulate Double-Bang events through phenomenological arguments, using muon neutrinos as primary particles and pions as the generators of the EAS which in principle may come from the tau decay.

Fig. 1 presents the different behavior of an EAS depending on the type of interaction and the inelasticity value. In each of the graphics of the figure we have 50 EAS's induced by muon-neutrino with energy $E = 0.5$ EeV and incident angle of 75°. The dashed orange lines are the average of the Gaisser-Hillas function [24] for each one of the simulations.

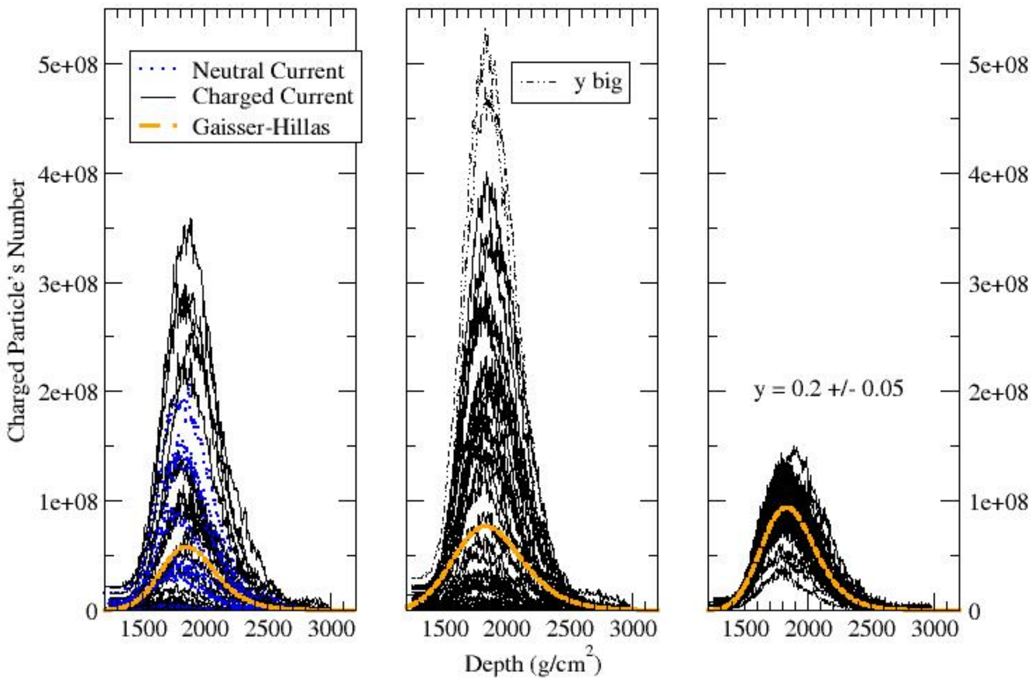

Figure 1: Charged particles as a function of atmospheric depth. Comparison of the kind of interaction of muon-neutrino induced events with energy $E = 0.5$ EeV. In the left side we have interactions randomly induced via Monte Carlo. In the center only CC interactions are present, and in the right side we have CC interactions with inelasticity $y = 0.2 \pm 0.05$.

On the left side of the Fig. 1 one has CC and NC interactions happening freely. Also the elasticity value is obtained randomly by Monte Carlo method with CORSIKA. We obtained 35 CC interactions (black continuous lines) and 15 NC interactions (blue dotted lines). As it is expected because of the bigger cross section, 70% of the interactions are CC interactions.

On the central part we present only CC interactions. There are two showers with bigger number of charged particles than in the simulations presented on the left side, but it may probably be because of statistical fluctuations. In average, for tau and muon-neutrino induced EAS's, one expects the same longitudinal profile for both CC and NC interactions. The difference as we have seen, beside the cross section difference between CC and NC, is that in the case of CC a charged lepton is created and for NC it is a neutrino.

The right side of the Fig. 1 has only EAS's generated via CC interaction and with inelasticity $y = 0.2 \pm 0.05$. Because the most part of the energy goes to the charged lepton, the EAS with hadronic nature has low energy. Moreover, because the inelasticity is basically fixed around one value, the maximum number of charged particles is concentrated around a fixed value too. For that value of inelasticity, the number of charged particles is around 10^8 particles. The Gaisser-Hillas function gives a good approximation with low deviation in this case. We can see that, as expected for these energies [25], for the two previous cases the average value of y is nearly the same, but with much bigger deviation from the average since the inelasticity is a free parameter chosen randomly.

3.1 Double-Bangs

The alternative we use to simulate events generated by tau-neutrinos in the atmosphere is to input muon-neutrino as primary particle. The main characteristics of muon and tau-neutrino induced events are the same with the exception that a muon-neutrino interacting via CC generates a muon. As we are simulating tau-neutrino interactions, we need the creation of a tau. To simulate the tau creation and subsequent decay we use pions. One can divide the tau decay in two main modes: 64% for the hadronic modes and 36% for the leptonic modes. In our simulations we consider only the hadronic modes in which the main decay products are pions. In this way we generate the second shower inputing the pion as primary particle in the same direction of the muon-neutrino, after a distance L corresponding to the tau mean lifetime and with the corresponding energy E_2 from Eqs. (9)-(10).

In Figs. 2, 3, and 4 we show events for the tau energy of approximately 0.4 EeV. It means that the tau should have run a distance of about 20 km from the neutrino interaction point until the tau decay, and considering, from Eq. (9), that 2/3 of the tau energy goes to the decay products, it corresponds to a pion energy of 0.27 EeV. Each graphic of the figures contain 10 Double-Bang events, that is to say 10 showers initiated by muon-neutrino and 10 initiated by pion (π^-).

In the bottom left of Fig. 3 we have a kind of fake Double-Bang event where the second EAS was not generated by the tau decay, but by some fragment of the first EAS that interacted or decayed after traveling a very long distance comparing with the mean distance traveled by the taus with 0.4 EeV energy.

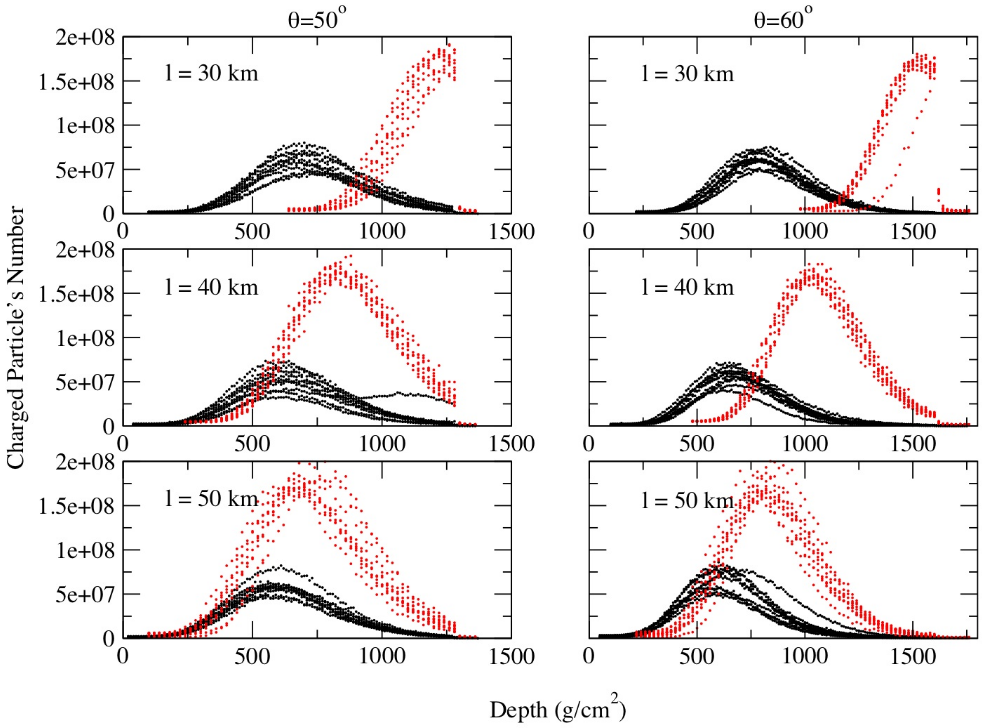

Figure 2: Double-Bangs generated by tau-neutrinos in the atmosphere. Each graphic contains ten events represented by the number of charged particles as a function of depth with primary neutrino energy of 0.5 EeV. The incident angle is of 50° in the fist column and 60° in the second one. The interaction depth is 30, 40 and 50 km respectively for each line. The first EAS's, with less than 10^8 charged particles, are represented in black and the second ones, due to the tau decay with more than the double number of particles, are represented in red.

To obtain the events generated by 0.5 EeV neutrinos depicted in Figs. 2 and 3 we use only inelasticity values of $y = 0.2 \pm 0.05$. In this way we have, from Eq. (4), $\langle E_1 \rangle \sim E_\nu/5$, and also from Eq. (10), $E_2 \approx 2.67 E_1$. Analyzing events coming from different angles and interaction depths, we may say which values of theses parameters are more favorable for detecting Double-Bang events.

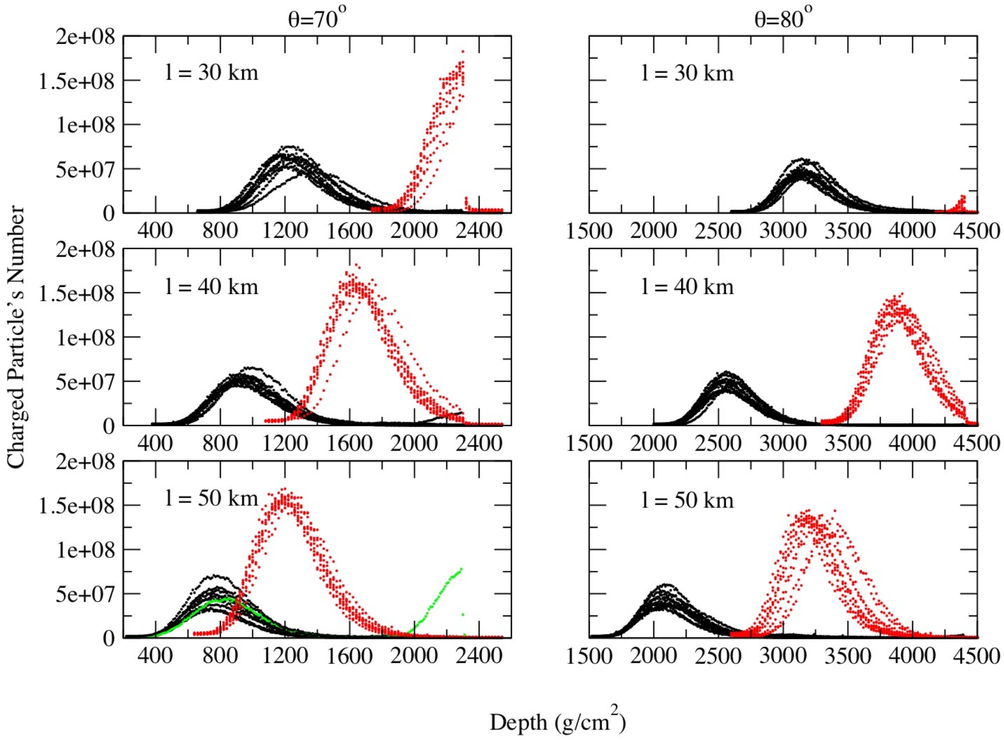

Figure 3: Double-Bangs generated by tau-neutrinos in the atmosphere. Each graphic contains ten events represented by the number of charged particles as a function of depth with neutrino energy of 0.5 EeV. The incident angle is of 70° in the fist column and 80° in the second one. The interaction depth is 30, 40 and 50 km respectively for each line. The first EAS's, with less than 10^8 charged particles, are represented in black and the second ones, due to the tau decay with more than the double number of particles, are represented in red.

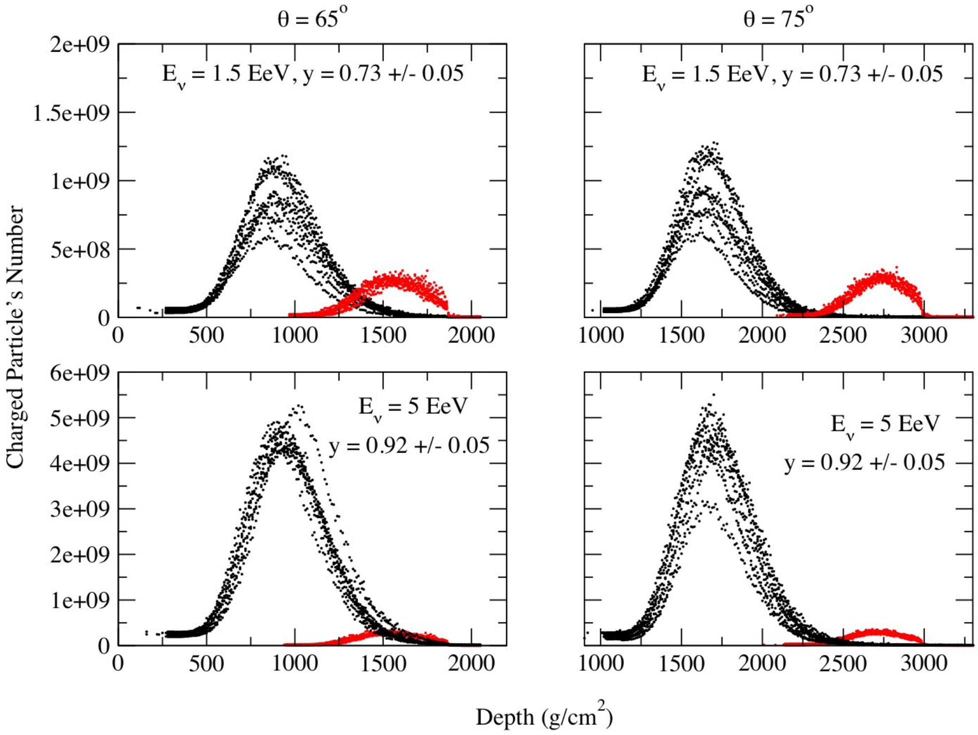

Figure 4: Double-Bangs generated by tau-neutrinos in the atmosphere. Each graphic contains ten events represented by the number of charged particles as a function of depth generated 35 km far from the ground. The incident angle is of 65° in the fist column and 75° in the second one. The neutrino energy is 1.5 EeV for the graphics in the first line and 5 EeV for the ones in the second line. The first EAS's, with bigger number of charged particles, are represented in black while the second ones, due to the tau decay, are represented in red.

In Fig. 4 we have events with more energy for the primary neutrino. In this case, due to the energy distribution between the first EAS and the charged lepton, we have the first EAS more energetic than the second one. For $E_\nu = 1.5$ EeV and $y = 0.73$, $E_1 = 1.1$ EeV $\approx 4E_2$. If the neutrino energy is $E_\nu = 5$ EeV and $y \approx 0.92$, than $E_1 = 4.6$ EeV $\approx 17E_2$.

Observing mainly the simulations in Figs. 2 and 3 we have the hint that the bigger is the incident angle, for neutrinos interacting always at the same distance from the detector, the bigger is the distance between the two maximums of the EAS's generated. Furthermore, the same happens diminishing the distance of the primary interaction to the detector. We conclude that the worse situations to detect Double-Bangs are for $l = 50$ km and $\theta = 50°$, as well as for $l = 30$ km and $\theta = 80°$. In the first situation the two EAS's overlap each other and in the second one, the second EAS reach the ground before it has a considerable number of particles. These effects may happen due to the different atmospheric density depending on the height. Close to the surface of the Earth, where the density is higher, the particles have more probability of interacting and consequently the longitudinal development of the EAS is faster.

4 Discussion

UHE neutrinos probably coming from extragalactic sources may interact in the atmosphere via NC or CC. The average inelasticity for energies of the order of 1 EeV for neutrino-nucleon interaction is $y \approx 0.2$. It means that for NC interactions one hadronic EAS is produced in average with approximately 20% of the energy of the primary neutrino while for CC interactions there are three distinct cases: (*i*) when an electron-neutrino interacts an electron is created which immediately starts an electromagnetic cascade. So, after electron-neutrino CC interactions it is created an EAS with one hadronic component bringing approximately 20% of the primary neutrino energy and one electromagnetic component with 80% of the energy of the primary neutrino. (*ii*) when a muon-neutrino interacts a muon is created which basically does not interact in the atmosphere and the EAS generated is similar to the one generated in a NC interaction. (*iii*) when a tau-neutrino interacts a tau is crated which decay in a distance comparable to the size of the hadronic EAS generated by the neutrino interaction. Nearly 64% of the times the tau decay generates a hadronic EAS and 18% of the times an electromagnetic one. Approximately 17% of the times the tau decay in muon and neutrinos that do not generate any cascade.

We simulate tau-neutrino induced events for three different energies with y values such that Double-Bang events can be observed. In the case of $E_\nu = 0.5$ EeV the expected inelasticity is compatible with the observation of the events because the average energy of the tau is $E_\tau \simeq 0.4$ EeV what corresponds to a distance travelled before decaying of $L \simeq 20$ km. For this energy the EAS that may be generated by the tau decay develops very close to the EAS created by the neutrino-nucleon interaction, but at the same time both EAS's are distinguishable. For the simulated energies of $E_\nu = 1.5$ EeV and $E_\nu = 5$ EeV, if we considere the expected inelasticity the energy of the tau is such that the tau decay does not happen inside the field of view of a supposed detector because it travels a very long distance before decaying. So we simulate events with values of y above the average for the tau energy to correspond to a travel distance of $L \simeq 20$ km. Despite those events are very unlike and may not be easily seen, they are still possible.

The profile os Double-Bang events may be observed by FD's such as those of the Pierre Auger Observatory or HiRes. The energy range must be very strict because to observe the two EAS's the energy cannot exceed about 1 EeV. But also the efficiency of the detector is an important factor and energies bellow 1 EeV are not optimal for the FD's to observe events. The ground arrays such as the Telescope Array and the Auger array may be another possibility to detect Double-Bangs. Almost horizontal Double-Bangs can develop both EAS's inside the array. And finally the other possibility is to use both technics, for example, observing the first shower with the FD and the second, due to the tau decay, with the ground array.

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